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earthquake P's for all recorded frequencies above 2 Hz, in spite of the fact that the average explosion magnitude is less than average earthquake magnitude. In the 2.5 to 2.9 Hz range explosion P's are at least 6 db higher than earthquake P's.

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TECHNICAL PROBLEM

High-frequency P_n and S_n are generally the most prominent phases recorded at mid-Pacific sites from circum-Pacific earthquakes within approximately 40° epicentral distance. Interest in the characteristics of these phases as a possible discriminant between explosions and earthquakes in the Kamchatka-Kuriles region resulted in an AFOSR contract with the University of Hawaii's Hawaii Institute of Geophysics (HIG), where research on these phases had been ongoing for several years. Objectives of this contract were to relate characteristics of the high-frequency P_n, S_n coda with focal depth, source functions and path parameters. A further objective which developed during the first year of this contract was to explore the capability of the hydrophone array located near Wake Island as a detector and discriminator of explosions at epicentral distances between 60° and 90° (the range of most existing Russian test sites) using the mantle-refracted P phase.

DATA BASE

During the first year of the project, existing data in several forms and from several sites was used to examine probable parameters influencing the generation and propagation of high-frequency P_n, S_n phases. Some results from these studies were reported in last year's technical report, have been published or are in press (1, 2, and 3). In July 1979, under the joint sponsorship of AFOSR and ONR-Earth Physics the hydrophone array at Wake Island was reactivated, and continuous tape recording of three of the sixteen available hydrophones began. The earthquake and explosion data collected using this system was intended to form the primary data base for

carrying out our objectives. This system has proven reliable, and as of January 1, 1981 nearly eighteen months of data had been collected.

The Wake tapes probably contain the largest suite of tape recorded P_n, S_n phases from a single site ever assembled. With this data many aspects of high frequency P_n, S_n phases are being examined in greater detail than ever before. These tapes also contain recordings of mantle-refracted P from at least 18 nuclear explosions at Russian test sites as well as from several shallow-focus earthquakes at approximately the same distance range. These phases form the basis for developing possible discriminate techniques at Wake.

EVALUATION OF THE WAKE RECORDING SYSTEM

A slow speed, gain ranging, 4 channel cassette recording system has now been in operation at Wake for nearly 18 months. This system continuously records three data channels and a time code channel at the rate of one cassette tape per week. There have been both advantages and disadvantages in using this type of recording system.

I. Advantages

A. Reliability

The only serious problem to develop thus far has been a malfunction in a gain controlled amplifier causing loss of data on one of the three data channels. Otherwise this remote recording system has proven to be extraordinarily reliable. Three key factors are responsible.

1. Existing technology and experience accumulated at HIG through the development of ocean bottom seismometer recording equipment was incorporated into this instrument.

2. The recording package at Wake is housed in an air-conditioned, positive pressure environment--an essential for electronic equipment at island sites.
3. A reliable support group at Wake, with the resources necessary to maintain both the instrument (effecting minor repairs when necessary) and its environment has been available.

B. Compact Data Format

Eighteen months of data are stored on approximately 75 cassette tapes which take up less than a cubic foot of space and are kept in a fireproof safe at HIG.

C. Simplicity of Operation

The operation, at Wake, of the recording system--changing batteries and tapes, making time corrections, and mailing the recorded tapes to HIG--consumes less than 3 hours per week.

The only supplies required, batteries, tapes and mailing envelopes, are sent to Wake from HIG roughly every six months. Very little effort outside of these normal operations has been necessary to keep the system running smoothly.

II. Disadvantages

A. Frequency Spreading

One disadvantage of the Wake slow speed analog recording system is the somewhat questionable fidelity of the recorded signal. Instabilities in the frequency domain caused by minute variations in the recording speed of the tape are exaggerated at slow speeds. These variations are partly reduced during digitization--by synchronizing the digitization rate with the recorded time code.

However, a study using recorded calibration signals indicate that a narrow band recorded signal may still be somewhat spread out after digitization as shown in Figure 1. In general, the magnitude of this effect was found to be down by more than 24 db at one octave away from the peak frequency of the signal.

B. Intermodulation Distortion

A common problem in most analog tape recording systems is intermodulation distortion, that is the non-linear mixing of two frequencies to produce a third frequency. This effect has not been evaluated for the Wake system.

C. Tape Skew

An important potential advantage of the Wake hydrophone installation is that it is a matched array. This makes it extremely useful for studies which compare the signals from one event on different hydrophones, provided that an accurate method of timing is used. Although our cassette recording system does record three data channels simultaneously with a very precise 10 Hz time code, the extremely slow tape speed exaggerates errors in alignment between the record and playback tape heads. Although adjustments are made during playback to minimize this effect, random timing errors of a 0.1 seconds between channels are not uncommon. Errors of this magnitude are not acceptable since they represent a quarter wavelength of an incoming signal at 2 Hz (the dominant frequency of nuclear shots thus far recorded).

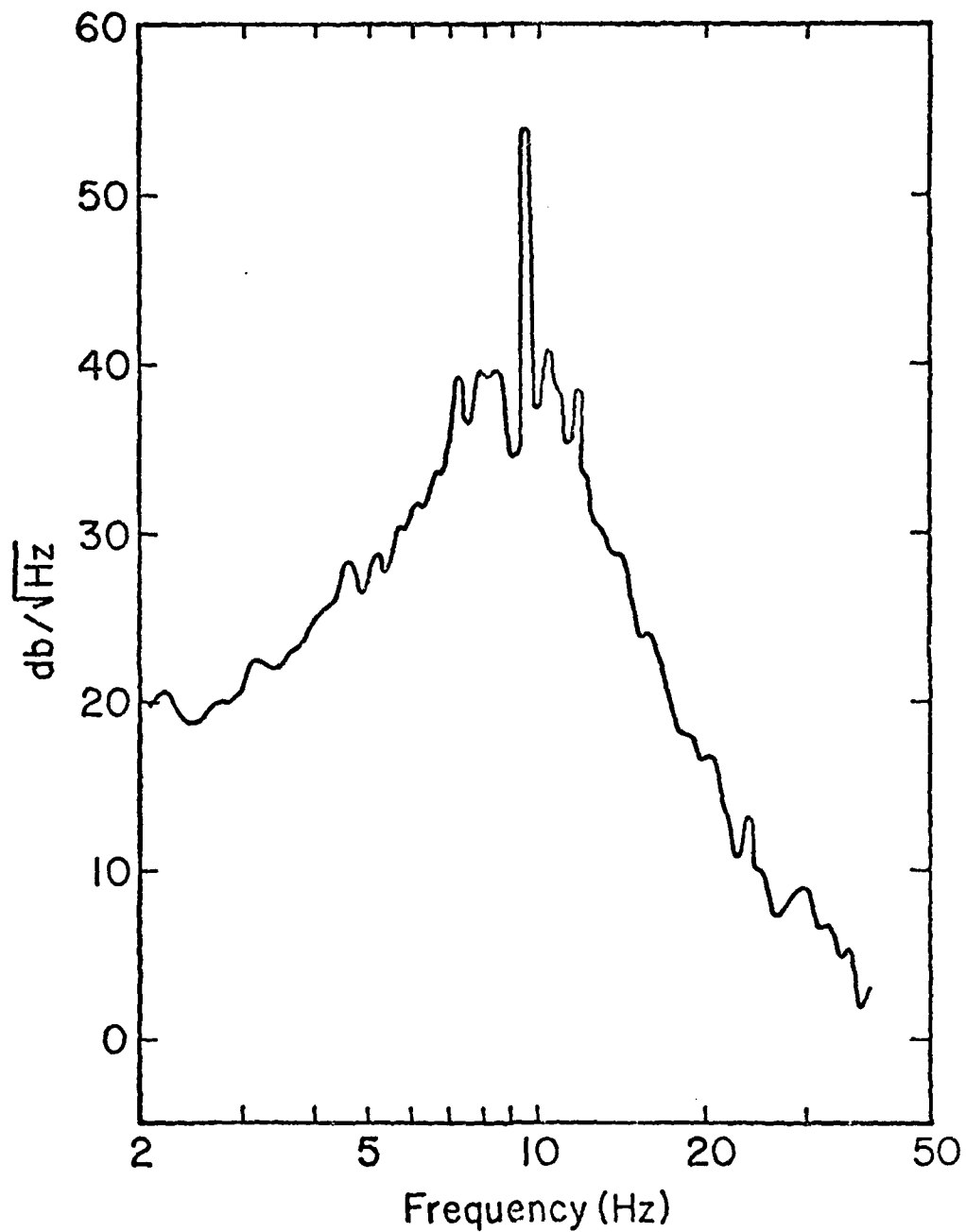


Figure 1. Spectrum of the played back signal which was recorded as a 10 Hz sine wave on the Wake slow speed cassette system. Note the spreading of frequency in this signal caused by small fluctuations in the recording speed.

D. Limited Dynamic Range

Another disadvantage is the limited dynamic range imposed by an analog recording scheme. The overall dynamic range of the tape is approximately 40 db from tape noise to dipping distortion levels. A gain ranging system sets the broad band (~ 0.5 -10 Hz) prewhitened noise level at approximately 20 db above tape noise. While this is advantageous for purposes of recording actual background noise at all frequencies so that small signals may be seen, it allows an overhead of only 20 db. An incoming signal larger than approximately ten times the broadband background noise level becomes distorted. Roughly 15% of the events we have recorded are affected in this way. Unfortunately, these larger signals would provide maximum information if recorded properly.

WAKE HYDROPHONE CALIBRATIONS

Efforts in trying to locate calibration curves or design blueprints for the Wake hydrophones have still proven fruitless for the most part. This past year however, some calibration curves of the Wake hydrophones for frequencies above 10 Hz (slightly higher than our main range of interest) were found. The shape and absolute level of these curves are very similar to the response curve of a coil hydrophone installed on a Columbia University ocean bottom seismometer (OBS) in 1966. Furthermore, the Columbia OBS hydrophone and the Wake hydrophones were manufactured by the same company at around the same time and have identical coil resistances. Based on this information, the response curve of the Columbia OBS hydrophone, which covers frequencies from 0.02-100 Hz, has been used to calibrate the signals at Wake.

TECHNICAL RESULTS

I. Background Noise Levels on the Wake Ocean Bottom Hydrophones

A high priority of ongoing research has been to make accurate measurements of the background noise levels in the deep ocean near Wake for frequencies between approximately 0.5 and 20.0 Hz. Confidence in a calibration curve for the Wake hydrophones has now made this possible. Some initial results are shown in Figure 2. Plotted in this figure is the range of noise measurements on one bottom hydrophone (~ 5.5 km depth) for 24 random one minute periods over the 18 months of operation at Wake (shaded region labelled A). Also plotted are an assortment of published noise curves for both ocean-bottom and continental sites which have been converted to the scale of db re 1 $\mu\text{bar}/\sqrt{\text{Hz}}$ by the following relationships:

$$1 \mu\text{m} \text{ (maximum particle amplitude)} \rightarrow (9.42 \times 10^{-2} \times \text{frequency in Hz})$$

$$\mu\text{bars} \text{ (maximum pressure variation)}$$

$$1 \text{ micron/sec} \text{ (maximum particle velocity)} \rightarrow 15 \mu\text{bars} \text{ (maximum pressure variation)}$$

$$1 \mu\text{Pa} \text{ (maximum pressure variation)} = 10^{-5} \mu\text{bars} \text{ (maximum pressure variation)}$$

Curves B, C, and D in Figure 2 are ocean bottom noise curves. B is a hypothetical "sample spectrum of deep-sea noise" (4). C is a vertical seismometer measurement made in the Mariana Basin (5). D is a vertical seismometer measurement made at 4.6 km depth between Hawaii and California (6).

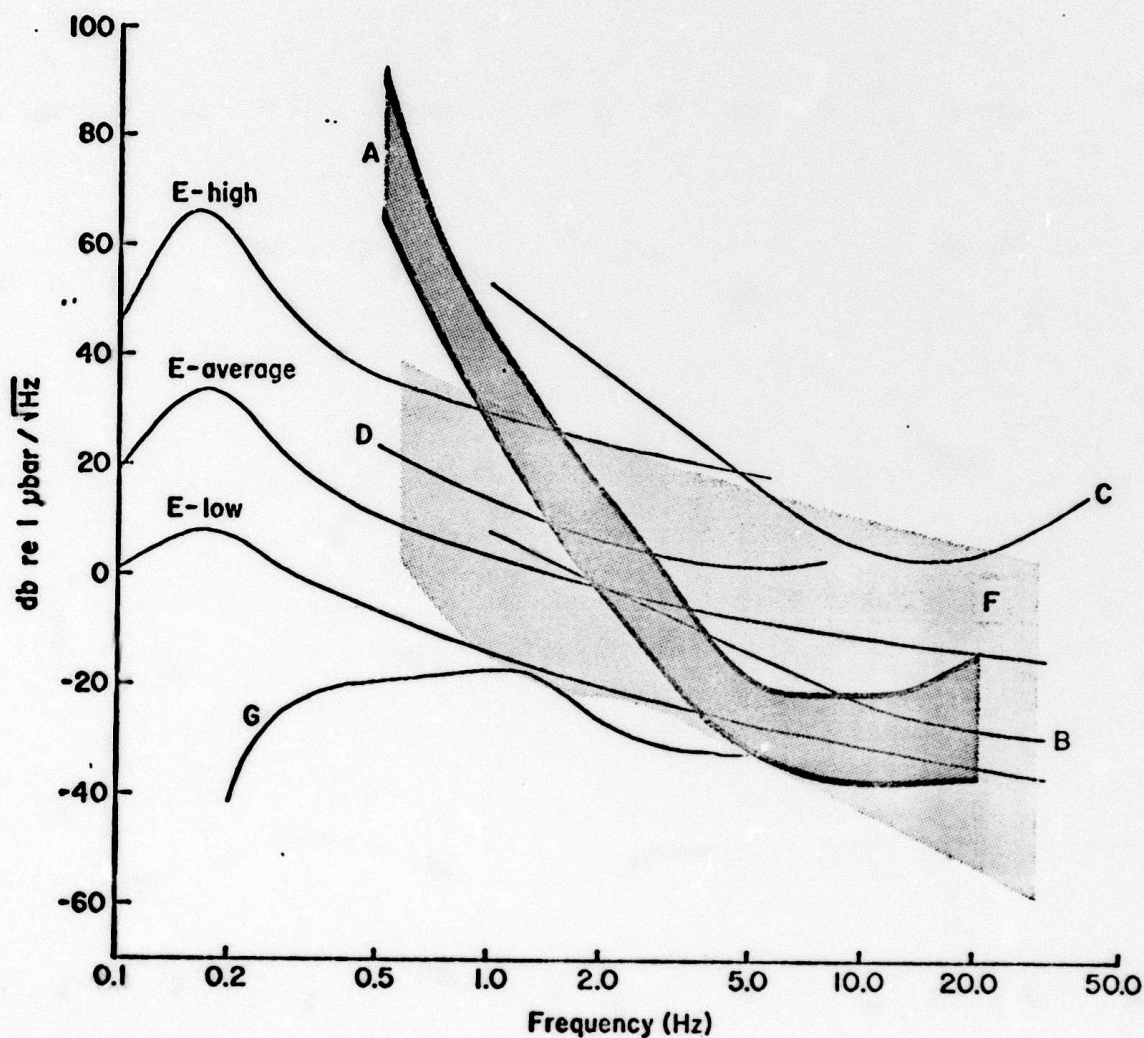


Figure 2. The range of background noise levels measured on the Wake bottom hydrophones (shaded region A) compared with other background noise levels measured on the ocean bottom (curves B, C, and D) and measured on continents (shaded region F, and curves E and G). More complete explanation of this figure is given in the text.

E, F, and G in Figure 2 are continental noise measurements. E is actually three curves representing low, average, and high noise levels for continental sites. These curves were compiled by Brune and Oliver (7) from previously published data. F (shaded region) is an area bounded by the limits of (and containing) noise curves measured by vertical seismometers for 16 locations within the United States and Germany (8). G is a noise curve for the Oyer subarray of the Norwegian Seismic Array measured during a period "when most of the North Atlantic Ocean was very quiet" (9). With respect to noise levels at continental sites, this study seems to show that the noise levels measured by hydrophones on the ocean bottom near Wake are:

1. very noisy to average for frequencies between 0.5-1.5 Hz
2. average for frequencies between 1.5-3.0 Hz
3. quiet for frequencies between 3.0-5.0 Hz
4. quiet to exceptionally quiet for frequencies between 5.0 and 20.0 Hz.

Further work is planned to more precisely show how the noise levels vary, and perhaps to understand the nature of this variation. Preliminary investigations have already indicated a correlation between surface wind speed and noise at frequencies above 4 Hz. This effect is predicted by Wilson (10) and was previously examined using Wake data collected over a short period of time in 1976 (11).

II. Shallow Focus P_n, S_n

As of June 1980, 48 earthquakes with P_n, S_n phases having a signal noise greater than 3:1 had been recorded at Wake. Of these 48 events, 29 had focal depths less than 200 km, and travel paths to Wake across the

Northwestern Pacific Basin. These events have been digitized, standardized to a uniform gain step, filtered from 4-8 Hz to enhance the P_n , S_n signals, and plotted. Maximum P_n and S_n amplitudes were measured from these plots for each event, and a combined amplitude equal to the square root of the sum of the squares of each two amplitudes was computed. These combined amplitudes were then scaled to a common event magnitude. Figure 3 is a plot of the scaled combined amplitudes versus epicentral distance, with event depths in kilometers noted by each point. Over the entire range of epicentral distances shown (18° to 36°) there does not appear to be a significant relationship between amplitude and depth. Shallow focus events (33 km or less) appear to be uniformly spread over the range of observed amplitudes for any given epicentral distance. Spectral analysis of these phases to determine possible depth dependence is in progress but has not yet been completed.

III. Discriminant Techniques using Mantle Refracted P at 60° to 90° Epicentral Distance

The work of Evernden (12), and Evernden and Kohler (13) at the LASA array has indicated that spectral characteristics of mantle refracted P at 60° to 90° epicentral distance may be used as an effective discriminant between earthquakes and Eurasian explosions. Data based on slow speed paper recordings of the Pacific Missile Range facility at Wake prior to 1975 (14) and data collected thus far by the reactivated ocean bottom hydrophones at Wake support this conclusion.

Figure 4 is a plot of the spectral characteristics of 8 explosions and 5 shallow focus earthquakes at 60° to 90° epicentral distance,

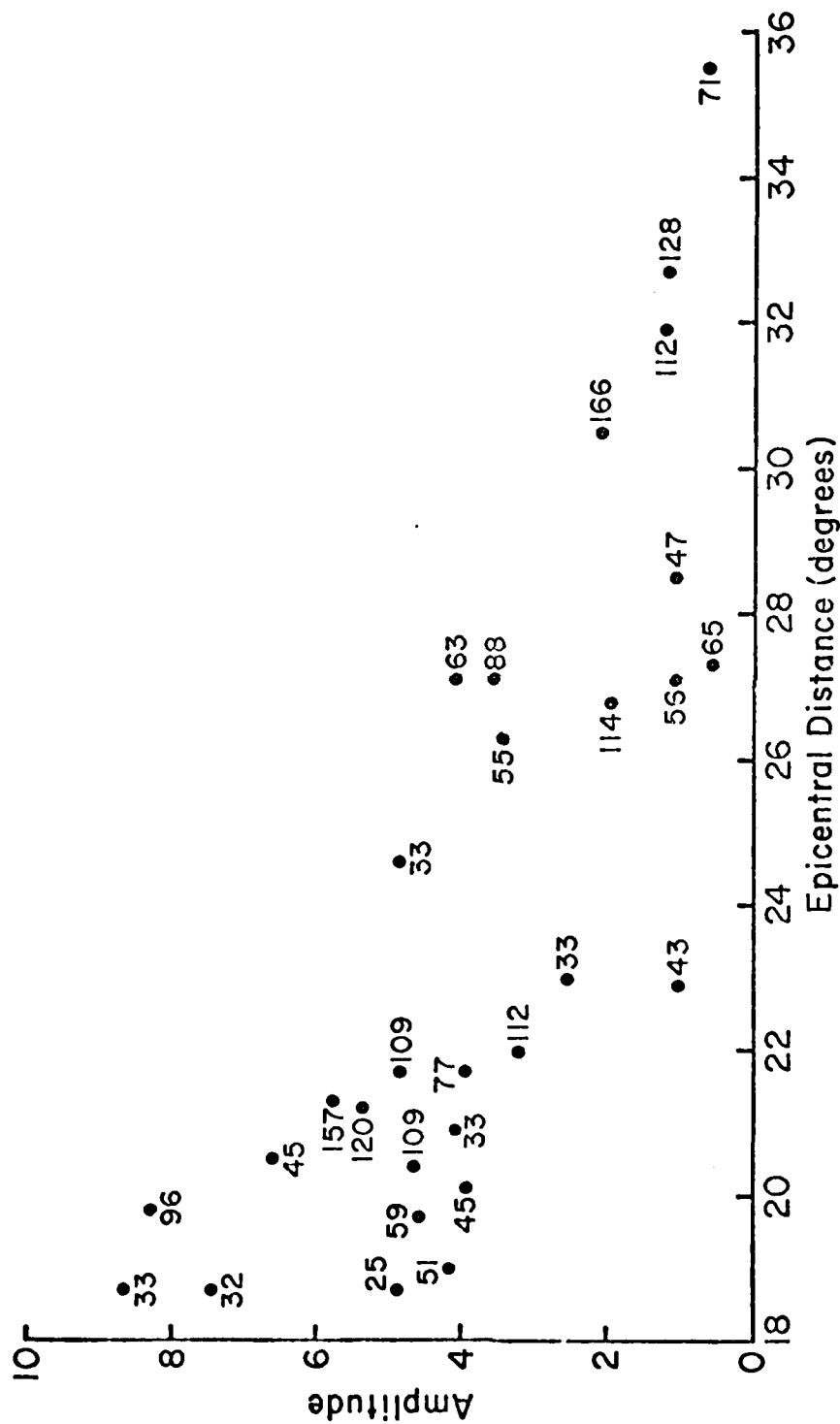


Figure 3. High frequency Pn and Sn maximum amplitudes combined as the square root of the sum of their squares, and normalized to a common magnitude are plotted against the epicentral distance to Wake of the event they represent. Numbers by each data point are the focal depths (km) of the event.

which had strong signal:noise and were not clipped during recording. Further description of these events is given in Table 1. The vertical scaling is the same for each curve, although they have been shifted to make them easier to see. The 0 db level relative to 1 microbar per square root Hertz has been noted for each curve. Only data points which were at least 4 db above the background noise level have been plotted. This figure clearly shows basic differences in the spectral signatures between explosions and shallow focus earthquakes.

1. There is a lack of energy in explosion P relative to earthquake P at frequencies below approximately 1.3 Hz.
2. Corner frequencies for explosions appear to be around 2 Hz while for earthquakes the corner frequencies, although not visible, are at least lower than 1.0 Hz.

In addition, average values for the 2.5 Hz and 2.9 Hz estimates are at least 6 db higher for the explosions in spite of the fact that the average explosion magnitude is less than the average earthquake magnitude.

These observations although important are not surprising. Similar findings have been reported in slightly differing forms by Wyss et al. (15), Dahlman and Israelson (16), Evernden (12), and Evernden and Kohler (13) for both U. S. and Eurasian explosions. The proven response of the Wake ocean bottom hydrophones to high-frequency seismic phases and the fact that these hydrophones lie within 60° to 90° of most of the world's nuclear test sites (Nevada, Tahiti, Novaya Zemlya, E. Kazakh, W. Kazakh, and Siberia) makes this an important result.

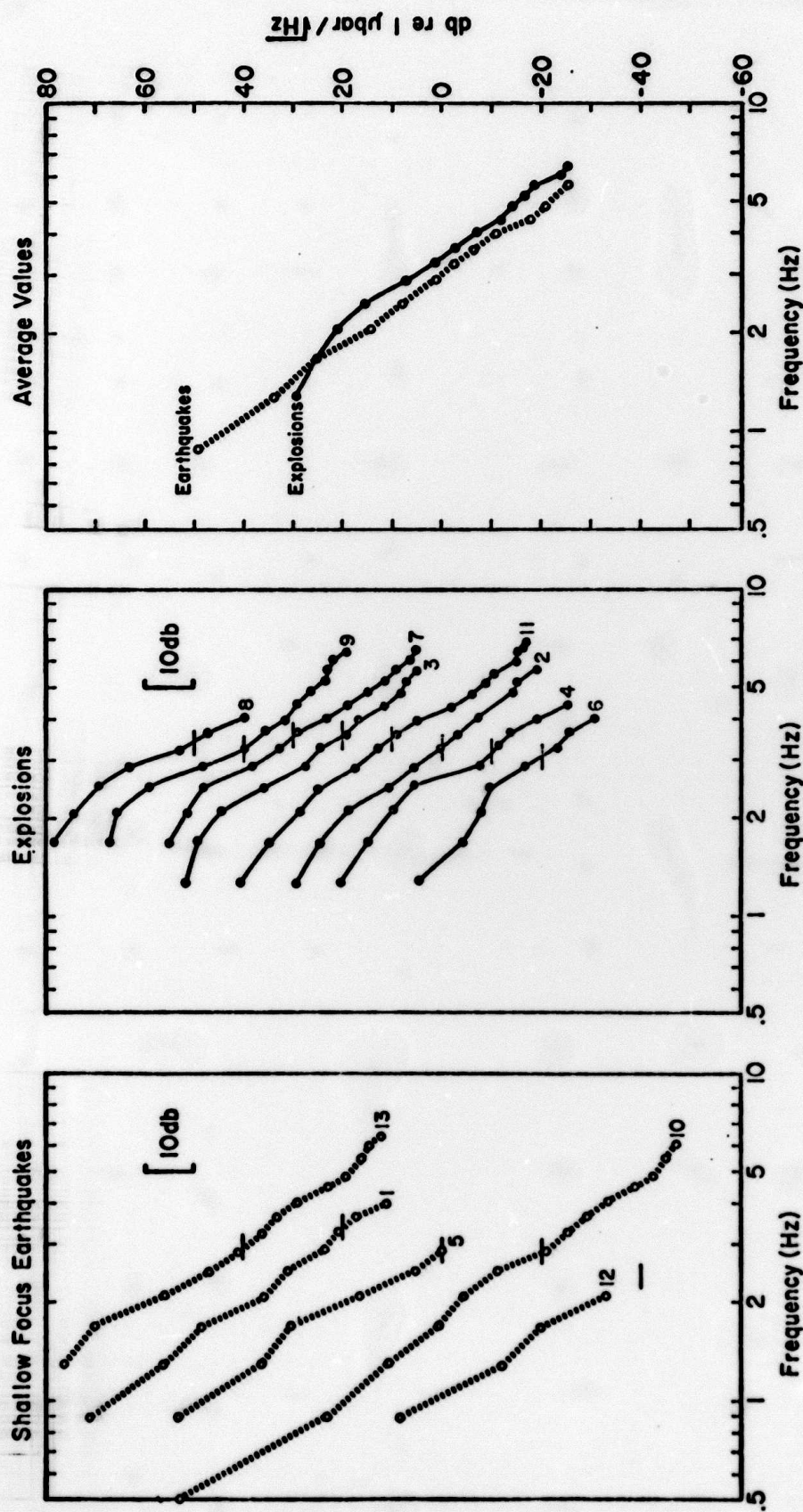


Figure 4. Spectrums for shallow earthquakes and explosions at 60° to 90° epicentral distance from Wake, along with a plot of average values for each group. A description of each event (event number is noted by each curve) is given in Table 1. The 0 db level for each curve is marked with a horizontal bar. Note the obvious differences between spectrums of earthquakes and explosions, made especially clear in the "averaged" plot.

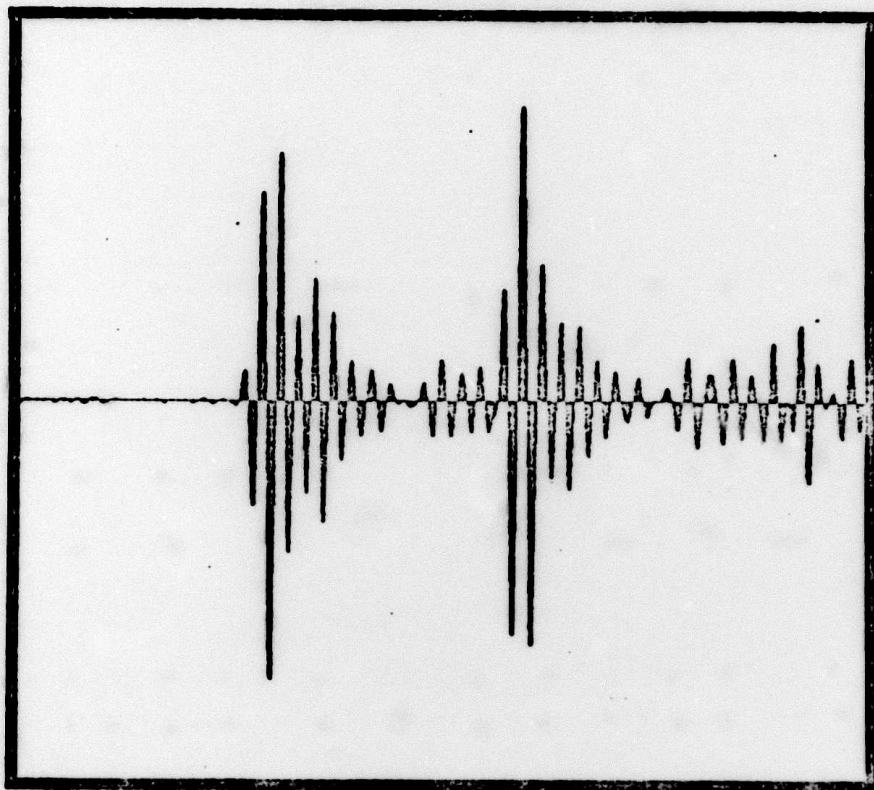
Table 1. Description of Events Used in Figure 4

Number	Date	Location	Distance (degrees)	Depth (km)	Magnitude (mb)	Type
1	07/24/79	S. of Java	65.7	31	6.3	Earthquake
2	08/04/79	E. Kazakh	73.2	0	6.1	Explosion
3	08/18/79	E. Kazakh	73.2	0	6.1	Explosion
4	09/24/79	Novaya Zemlya	76.7	0	5.7	Explosion
5	09/29/79	N. Sumatra	72.9	27	6.2	Earthquake
6	10/18/79	Novaya Zemlya	76.8	0	5.8	Explosion
7	10/28/79	E. Kazakh	73.2	0	6.0	Explosion
8	12/02/79	E. Kazakh	73.3	0	6.0	Explosion
9	12/33/79	E. Kazakh	73.3	0	6.2	Explosion
10	07/29/80	Nepal	76.4	18	6.1	Earthquake
11	10/12/80	E. Kazakh	73.2	0	5.9	Explosion
12	11/08/80	N. California	61.5	14	6.2	Earthquake
13	11/19/80	Sikkim	70.4	33	6.0	Earthquake

IV. Detection of Small Magnitude Explosions

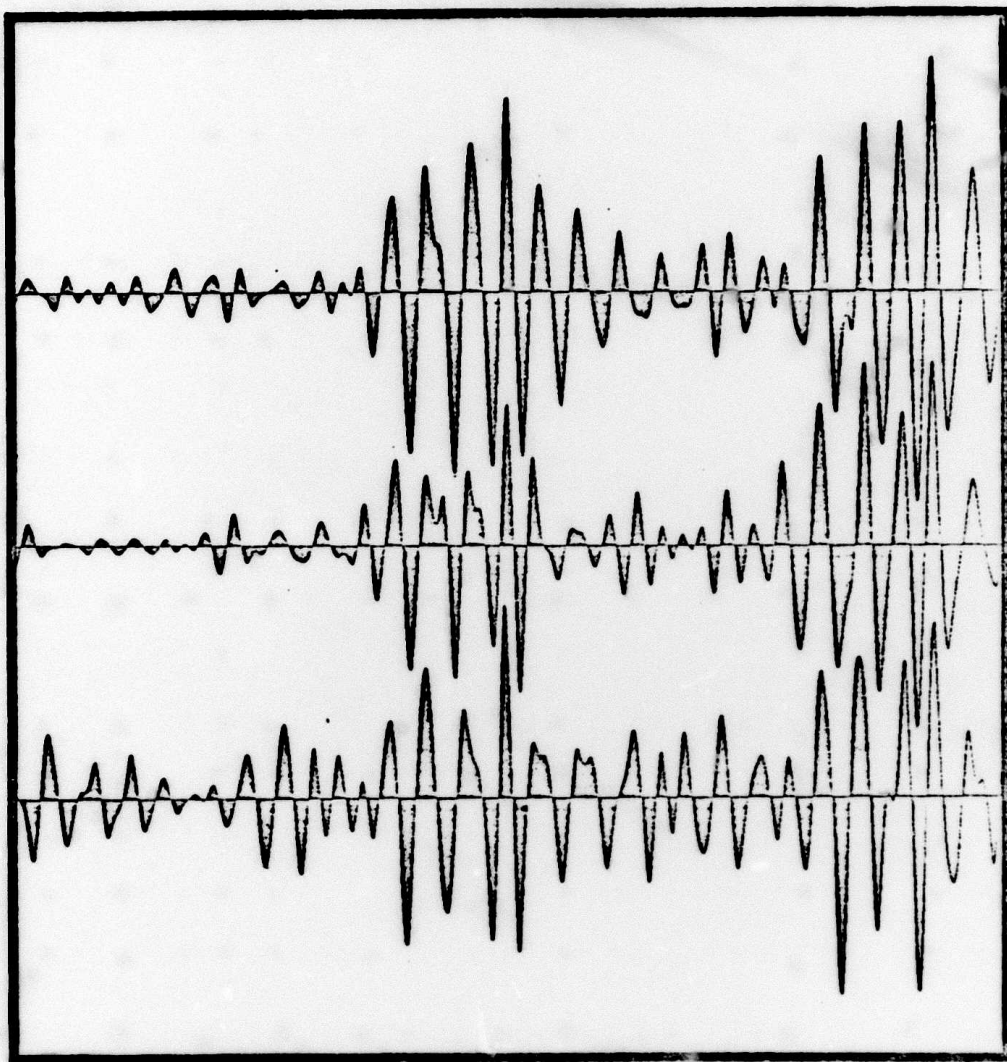
During eighteen months of operation so far, the explosion recorded with the greatest signal:noise, 50:1, was an Eastern Kazakh shot at 73° epicentral distance with a reported body-wave magnitude of 5.9. This signal:noise was measured from a digitized FM recording shown in Figure 5. Although several other shots from this region have been reported with equal or larger magnitudes, none has had a signal:noise quite as large. This may be due to the lower fidelity of the cassette recording system as previously discussed, as well as clipping of some shots, and increases in the background noise level during others. The smallest magnitude shot thus far detected was from Siberia, at 52° epicentral distance, with a reported body-wave magnitude of 4.9, and a signal:noise of 2:1.

It would be useful to project the size of signal that could be routinely detected if the Wake array were fully operational, with at least the six bottom hydrophones being recorded accurately. A gain in signal:noise of 2.4 ($\sqrt{6}$) is theoretically obtainable by simply adding signals from the six hydrophones with appropriate timing delays and transfer functions. Figure 6 illustrates the strong coherence between signals recorded on different bottom hydrophones. If a signal:noise of 2:1 is the minimum required for detection, then a signal 61 (i.e. $50\sqrt{6}/2 = 61$) times smaller in amplitude than the one received from the Eastern Kazakh event should be detectable. In terms of magnitude, an event 1.8 [$\log_{10}(61) = 1.8$; from the relationship given by Richter (17)] magnitudes smaller than 5.9--a magnitude 4.1--should be detectable (17). Considering variations in background noise levels as well as imperfections



Explosion 7 July 79 E.Kazakh 73.1°
m=5.9 1.8Hz octave bandwidth filter

Figure 5. Wake bottom hydrophone signal of an explosion which was recorded on an FM tape recorder. Note the large signal:noise.



Explosion 4 August 79 E. Kazakh 73.2° m = 6.1
1.0-3.0Hz filter

Figure 6. Three Wake bottom hydrophone signals of an explosion which was recorded on a slow speed analog cassette recorder. Note the remarkable coherence of the signals.

in signal correlations between hydrophones, a more realistic estimate of the minimum magnitude of routinely detectable shots from that region would be somewhat higher.

V. Results from other Experiments

- A. Easter Island. The special high frequency tape recording seismograph which had been in operation for two years at Easter Island was deactivated during 1980. Numerous instrumental malfunctions and maintenance difficulties, as well as high background noise levels reduced the anticipated usefulness of this station to AFOSR. No nuclear shots or shallow focus P_n, S_n phases were recorded.
- B. ROSE and Cocos Plate OBS experiments. P_n, S_n data from OBS's deployed on or near the Cocos Plate have been analyzed. A report on this data, now in press (3), suggests a relationship between high frequency P_n, S_n velocity and lithospheric age. Unfortunately, the nature of this data, collected over assorted geotectonic regimes by various unmatched and hard to calibrate sensors, made only the simplest studies possible. Accurate comparisons between P_n, S_n coda for various depth events could not be made.

REPORT SUMMARY

Interest in high-frequency P_n, S_n seismic phases as a possible discriminator between earthquakes and explosions in the Kamchatka-Kuriles region resulted in an AFOSR contract with the University of Hawaii, where research on these phases had been in progress for several years. An important aspect of this contract was the reactivation of the Wake hydrophone array (which took place in July, 1979) for the purpose of collecting high quality tape recorded P_n, S_n data. Subsequent to this reactivation, the Wake array was found to also be a potentially excellent receptor for mantle-refracted P arrivals from underground test explosions at 60° to 90° degrees epicentral distance (see Figure 5). Investigation of this potential as well as the development of discriminate techniques using the P phase is now underway in addition to continuing research on high frequency P_n, S_n .

Many aspects of high-frequency P_n, S_n generation and propagation are not well understood. Travel time data indicate that it propagates in a waveguide located in either the lower crust, the upper mantle, or both. The prominence of these phases on seismograms from stations in the Northwestern Pacific Basin, and their complexity of character suggest that they may carry enough information to be a useful discriminator between earthquakes and explosions in the Kamchatka-Kuriles region. Relationships of focal depth, source mechanisms and path parameters with the P_n, S_n character have been slow to emerge. Much of previously collected data is in the form of miscellaneous paper recordings which have been difficult to compare. However, the tape recorded data collected over 18 months at Wake includes P_n, S_n phases from at least 48 earthquakes, and is probably the largest suite of P_n, S_n phases on magnetic tape ever assembled. A preliminary study

of maximum amplitudes using the Wake data indicates that the relationship to focal depth may be subtle. Spectral studies using these data are under way. In addition, modelling by computer synthetics is continuing at the University of Hawaii under the sponsorship of ONR-Code 483, and the Wake data will be important for comparison. Although a method of discrimination between explosions and earthquakes using high-frequency Pn, Sn has not yet been found, investigations using this high quality data base are continuing.

Mantle refracted P phases from more than 18 explosions as well as several shallow-focus earthquakes, at 60° to 90° epicentral distance (a "window" for efficient seismic wave propagation) have been recorded at Wake. A comparison of the spectra of these phases indicate that existing methods [described by Dahlman and Israelson (16)] are probably adequate for discrimination of at least the larger explosions with high signal:noise. Although the recording system currently at Wake is not adequate for testing accurately the sensitivity of this array, projections indicate that explosions with magnitudes of 4.1 may be detected. Background noise levels measured on the bottom hydrophones at Wake indicate that it is as quiet or quieter than the best continental sites for frequencies above 4 Hz. This is important because some models for explosion source functions actually predict more energy at frequencies above 4 Hz for a 10 kiloton shot than for a 1000 kiloton shot (16), and because these frequencies have already been recorded for large magnitude explosions (see figure 4). Attempts will be made during the coming year using known or possibly new methods, to develop an actual discrimination technique, and to find the lower limits of our detection capability within the constraints of the present recording system using array techniques.

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